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Dealing with uncertainty and pursuing superior technology options in risk management—The inherency risk analysis

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ABSTRACT

Current regulatory systems focus on the state of scientific evidence as the predominant factor for how to handle risks to human health and the environment. However, production and assessment of risk information are costly and time-consuming, and firms have an intrinsic disincentive to produce and distribute information about risks of their products as this could endanger their production opportunities and sales. An emphasis on more or better science may result in insufficient thought and attention going into the exploration of technology alternatives, and that risk management policies miss out on the possible achievement of a more favorable set of consequences.

In this article, a method is proposed that combines risk assessment with the search for alternative technological options as a part of the risk management procedure. The method proposed is the inherency risk analysis where the first stage focuses on the original agent subject to investigation, the second stage focuses on identifying technological options whereas the third stage reviews the different alternatives, searching for the most attractive tradeoffs between costs and inherent safety. This is then used as a fundament for deciding which technology option to pursue.

This method aims at providing a solution-focused, systematic technology-based approach for addressing and setting priorities for environmental problems. By combining risk assessment with a structured approach to identify superior technology options within a risk management system, the result could very well be a win–win situation for both company and the environment.

1. Introduction

Risk can be seen as a natural consequence of an activity and it may seem impossible to imagine a life without risk. Within the notion of risk there are both opportunities and life-improving innovations, but also effects to those that have little or no share in the benefits of the activity in question. Consequently, one of the priority tasks of policy is to take measures to handle risks. Current regulatory systems focus on the state of evidence as the predominant factor for how to handle risks. The technical risk assessment is a fundamental component of the system and considers risk as a function of the inherent danger of an event occurring and the likelihood that the event will occur.

However, instead of allocating all resources to generate information on present hazards, resources should in parallel also go to generate information related to safer technology alternatives [1–3]. Technological change is generally seen as the major component in achieving a sustainable environment. However, the aspects of managing risks and generating safer technologies are often seen as two different activities that are normally not combined in regulatory procedures or industrial risk management [2]. This study therefore proposes a method that combines risk assessment with the search for alternative technological options as a part of the risk management procedure. The method proposed is the inherency risk analysis (IRA).

The first part of this article gives an introduction to the traditional risk assessment methodology asked for by regulatory bodies. It thereafter introduces the current regulatory tools for pursuing technology change within industry. In the second part, the concept of inherency is introduced, which is based on various approaches that all aim at reducing the capacity of an agent to cause harm. Many of these alternative approaches are systematized and incorporated in the inherency risk analysis presented in the third part of this article. The fourth and last part discusses different aspects of the methodology before a conclusion is provided.

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1.1. The traditional risk assessment

The traditional risk assessment methodology was developed in 1983 by the US National Academy of Science (NAS) and consists of the following stages [4]:

1. Hazard identification: what dangers may arise from the agent in question?
2. Dose–response assessment: what quantitative connections exist between the agent and the extent of the expected effect?
3. Exposure assessment: to what extent is the subject of protection exposed to the agent?
4. Risk characterization: what is the nature and magnitude of the risk?

This approach has formed the basis of many chemicals legislations, as for example both the new (REACH) and existing ones in the EU, but does not fit well with site-specific or process/plant risk assessment [5]. In site-specific assessments the extra step of how, why and when hazards are going into the environment is required. Furthermore the NAS-approach excludes the step of risk evaluation, the examination of what the assessment means in practice taking social aspects such as risk perception into account. Nevertheless, the traditional type of risk assessment needs information on three basic elements which can be viewed as generic to all type of technologies, innovations, substances or products when assessing the environmental impacts: (1) the properties; (2) the amount; and (3) the exposure of "the environment".

However, the traditional risk assessment tends to treat uncertainty as a mere incomplete definition of a cause–effect system and implies that more knowledge of that system is the route to control the risk [6]. The way that uncertainties (e.g. the use of most sensitive species, the application of uncertainty factors, and worst-case assumptions) are treated mean that it is possible for its conclusions to be attacked as overestimations or oppositely as underestimations of risks [7]. Thus, even in the cases where there are much data, there may be little consensus as to what the risks actually are. Risk assessment relies on scientific data on exposure and effects, but also on case-by-case assumptions based on expert judgment. The extension of the traditional risk assessment with experts providing judgments on different parts of the exposure–response paradigm have been suggested in situations where little quantitative information is available [8]. However, this exercise can take us only so far. The outcome of the exercises will depend on the selection procedure and constellation of the experts and furthermore cannot tell us what we do not already know and consequently handles the challenge of ignorance unsatisfactory. Nevertheless, it may be an attractive alternative to running toxicity tests as the estimated costs for assessing short-term toxicity range from $50,000 to $280,000 and the cost of skin sensitization testing range from $2800 to $3000 [9]. The likelihood that firms, especially SMEs, will have the financial and/or human capacity to carry out the range of toxicity tests normally called for by governmental agencies and/or conduct expert workshops with high quality yield is questionable. Production and assessment of risk information are costly and time-consuming, and furthermore, firms have an intrinsic disincentive to produce and distribute information about risks of their products as this could endanger their production opportunities and sales [1]. The potential costs compared to the effectiveness of traditional risk assessment schemes do not provide SMEs or larger firms high incentives for enthusiastically embarking on this task.

The goal of the risk assessment process can be seen as to evaluate the seriousness (probability and extent of damage) of the harm. However, in addition should criteria like incertitude (related to statistical or fuzzy uncertainty and ignorance), reversibility (possibility to restore the situation), delay effects (long time latency between event and impact) be taken into account [10]. The typical decision maker in governments has thus a difficult task: All decisions should be based on a scientifically reliable foundation regarding environmental risks, be socially acceptable, but also economically viable. There is no doubt that this often implies tradeoffs for different interest groups.

As an alternative to the traditional cost–benefit analysis, tradeoff analysis evaluates consequences systematically, describing all effects in their natural units, and with the time period in which each effect is anticipated clearly stated [3]. Economic effects are expressed in monetary units, health and safety effects are expressed in mortality and morbidity terms and environmental effects are for example expressed in damage to eco-systems. Unlike cost–benefit analysis are future effects not discounted to present value. Furthermore all uncertainties are fully described (risk, probability distributions, and indeterminancy) and not aggregated into a single benefit or cost stream nor assigned a monetary value as in the cost–benefit analysis. The decision maker must explicitly express any decision in terms of for example trading costs to consumers for a variety of benefits to citizens over several generations [2]. The tradeoff analysis can therefore be used as a fundament to make policy choices in a transparent manner. The policy consequences of different actors should all be visualized where risk assessment procedures can inform the tradeoff analysis on health and environmental effects. Also actors with no relationship with producers should be included.

Tradeoff analysis can very well be used as an input to clearly visualize the societal distribution of possible costs and benefits in the decision making process. Besides the scientific aspects, risk management should also include societal aspects such as *ubiquity* which is the geographical dispersion of potential damage and deals with intragenerational justice, *persistency* which is the temporal extension of potential damage and deals with intergenerational justice and *potential of mobilization* which can be understood as violation of individual, social or cultural interests and values [10]. As an addition to purely analytical procedures, involving stakeholders and an interested public in designing risk management strategies based on knowledge and value system of each stakeholder has been proposed [11]. This can be particularly important for ensuring that the most important considerations in the tradeoff analyses are included. However, how to implement this framework in day-to-day practice is still disputed [12]. Nevertheless, such an approach could be especially attractive in issues where there is little trust in the regulator. When there is trust in the regulator, in the respect that the regulator sufficiently addresses the different stakeholder tradeoffs, top-down risk communication could be a more effective alternative [13].

1.2. Incentives for technology change by regulatory procedures

Unfortunately, an emphasis on more or better science may result in insufficient thought and attention going into the exploration of alternatives, and that risk management policies miss out the possible achievement of a more favorable set of consequences [14]. Consequently should the different technological options for preventing, arresting, reversing or mitigating possible harm and the opportunity costs of selecting a given policy option be evaluated [3]. Some of the most common policy instruments for regulating industrial products, processes or services are command and control, voluntary initiatives, economic incentives, information disclosure and liability laws.

Command and control policies are rules reinforced by legal sanctions. The strength lies in the use of law to decide what is acceptable.

Its weaknesses are that it involves a high level of intervention in management, has a lot of "red tape", is expensive to enforce and administer with high standard and rule-setting costs and that it only demands compliance rather than the best level of risk avoidance. For example regulations which force the application of Best Available Technology (BAT) standards can be seen as to have a mere diffusion driven pollution prevention approach with the adaptation of technologies that exists elsewhere and is only new to the firm [15]. It requires lengthy procedures as the government has to continuously update the BAT standard and the BAT may have lost its progressiveness by the time its introduction is binding. A firm that considers only off-the-shelf technological options, does not require a cultural shift towards developing new technologies, with other words towards innovation [2]. Furthermore, the choice of processes and products depends mostly on the know-how a company has gained over time resulting in incremental improvements, whereas radical innovations deploy new areas of technology [15]. As willingness, opportunity, and capacity are together the critical factors for a firm undertaking technological choice, a company's attitudes and knowledge about what changes are possible has to be addressed when developing polices [2]. Therefore, setting parameters that force companies to look into new areas of technology are important considerations for policy makers. In addition, a firm that makes a substantial innovation creates knowledge during this process that might help about further improvements. These intertemporal spillovers may make innovations cheaper than relying on existing alternatives as firms learn to improve their evolving technology ([16], p. 87).

Voluntary risk management initiatives are often called for as industry arguably has the main responsibility for the safety of their activities. Such voluntary initiatives can in general be divided into (a) negotiated policy strategies between state and industry or (b) industry initiated codes of good practice. The proponents of voluntary initiatives and self-regulation argue that it has a high commitment by the involved parties, that the rulemakers and enforcers are always well informed, that informal and formal controls are easily combined, and that it involves low public costs. It may also challenge outdated and inefficient organizational routines, create opportunities for differentiation, and complementing firms' resource investment patterns [17]. Its opponents argue that it is secretive, unaccountable and poorly enforced. In addition may a governmental oversight be needed which can lead to bureaucratic and cost duplications as well as policy confusions. However, the successful voluntary agreement has to be based on publicly decided goals, with transparency in the negotiation process and existing sanctions for non-compliance as well as instruments to deal with free-riders [18].

Economic incentives—such regimes are seen to allow high managerial freedom, as involving incentives to reduce risks to zero and as requiring low cost enforcement. However they may have complex rules, assume high degree of rationality from the regulated and thus predicting outcome is difficult, have large regulatory time delays and are politically sensitive as they allow risk creators a choice whether not to reduce risk if they can afford to pay the relative costs. In general, policies based on economic incentives seem to be more likely to prompt innovations for pollution prevention whereas judicial requirements favor end-of-pipe technologies [15]. Innovations for pollution prevention have furthermore the potential to disrupt environmentally destructive technological patterns with many components, whereas end-of-pipe technologies address to a larger extent only single components. The enforcement of regulations could also be made soft where firms have made an unsuccessful, but good attempt to comply with the regulations as it stimulates innovations by decreases the risk of a firm to adopt new technologies in the event of failure [2].

Disclosure polices are legally enforced requirements that operators or service providers supply information to the public. This give consumers or state institutions information on the high risk/low cost or low risk/high cost profile of a product. It involves low levels of intervention and can be seen as democratic. The disclosure of information can furthermore motivate firms to search for safer alternatives by public or market pressure. However, the users of the information may make mistakes in its interpretation and the quality of the information may also be sparse, unreliable or unintelligible. The effectiveness of these types of polices therefore depends on the information value to the different stakeholders and their reactions [1].

Rights and liabilities laws give certain parties the right not to be exposed to stipulated risks and the right to sue risk creators or harm causers. This has already proved effective for reducing post-consumer waste in several European countries and have had a major impact on industry in the USA [19]. They operate as *ex-post*-pricing systems for environmental harms, assessing harms that result from given activities and charging polluters the cost of compensating that damage [20]. In theory, the threat of a lawsuit will make the polluter to internalize the cost of the expected damage and to take optimal precautions. Liability laws may also involve low public expenditure. However, enforcing the rights may be expensive and establishing who created which risk may be difficult. Thus, victims may be unwilling to go to law. Furthermore, suit may not always be pursued against injurers, risk creators may be insured and thus may their own incentives to control risks be limited, bankruptcy provides an incentive for underprotection, and uncertainty regarding the legal standard leads to over- or underprotection depending on the circumstances [21]. For example, in the case of chemical hazards there is a case of gross underdeterrence by firms and therefore few-to-modest incentives to engage in preventative activities or innovations [22]. These laws may therefore be inappropriate with high risks and where preventative measures are needed. Such polices therefore still frequently combine liability with *ex-ante* safety regulation to compensate for these problems.

Forcing the search for safer alternatives at an early stage in the process may have both environmental as well as economical benefits. According to Ashford [2] this can be done through systematically implementing technology options analysis (TOA). The TOA identifies and documents the impacts of a technology option and compare improvements that each option might offer over the existing technology. The TOA goes beyond a multivariate impact assessment as it enables the possibility of performing comparative analyses of cost, environmental, health and safety analysis. Such a comparative technology performance and relative risk and ecological assessment are easier and more reliable to initial assumptions than analysis requiring absolute quantification of variables and are more likely to identify win–win options. Though TOA, technologies can be diffused into greater use within the industrial sector or identify technologies that might be transferred from other sectors. In addition, opportunities for innovation can be identified. However, governments have to require TOA in firms or conduct TOA themselves in order to facilitate major technological change [2]. This is because if governments undertake a mere technology assessment (TA) relying on technologies that industry itself puts forward, opportunities to foster superior technology options might be missed.

A TOA is also attractive for a SME because a fraction of the cost of conducting animal toxicity studies could yield extensive knowledge concerning what kinds of technology options exist or are likely to exist in the future. In contrast, in the case of highly polluting technologies are the existing markets dominated by powerful and mature firms that block changes necessary for advancement [2]. These firms will not encourage new entrants and competitors that are likely to displace their ineffective technology systems. Technology options based regulations can therefore stimulate innovations and open up new markets for SMEs that were previously blocked by large firms. This is an important consideration as the SMEs play an important role in developing innovations and contribute to the majority of new firm jobs [23].

2. Inherency risk analysis

A framework for providing a solution-focused, technology-based approach for addressing and setting priorities for environmental problems is needed. Instead of allocating all resources to generate information on present hazards (the risk-based strategy), resources should in parallel also go to generate information related to safer alternatives which include input substitution, final product reformation, and process changes [1]. Furthermore, requirements for firms to disclose risk information to the public can motivate firms to search for safer alternatives by public or market pressure. Technology-based regulations can in this sense stimulate significant fundamental changes in product and process technology which benefits the industrial innovator. Such a framework could very well be based on an 'inherency risk analysis'.

Inherency is already implicit in the first step of the traditional chemical risk assessment, the hazard identification. Article 2 of the European Commission Directive 93/67/EEC states that "*'hazard identification' is the identification of the adverse effects which a substance has an inherent capacity to cause*" [24] and in the regulation concerning REACH [25]: "*When it is not possible to establish the quantitative dose (concentration)–response (effect) relationship, then this should be justified and a semi-quantitative or qualitative analysis shall be included... In such cases it suffices to determine whether and to which degree the substance has an inherent capacity to cause the effect*." However, in practice it is conducted by the "effects assessment" which investigates the relationship between the magnitude of those effects and the dose to which an organism is exposed [7]. The multiple uncertainties in chemical risk assessment make it possible to argue that the risks are overestimated due to the test species applied, the application of uncertainty factors as well as worst-case assumptions about exposure, but it is also possible to argue that the due to the many uncertainties risk assessment methods underestimate the risks. As regulations currently are based on scientific consensus on risk of harm, substances which knowledge border the realm of ignorance are in general allowed continued production. The current risk assessment of chemicals cannot deal with the problem of ignorance as the process concludes there is no risk if the nature of the harm cannot be identified [7]. This study therefore suggests that pursuing the concept of inherency and its related risk may provide an effective orientation of the potential of a substance, product, process or system (hereby called agent) to cause harm. The general assumption is that the agent has a possibility to cause harm, which will encompass the concept of ignorance as it does not rule out a cause–effect relationship simply because we do not know and do not think it is probable.

2.1. The concept of inherency

Inherency as a concept is already implicitly applied in different approaches such as in green engineering, safety science and green chemistry.

In green engineering, inherency takes on a systemic dimension and inherent safety is seen as preferable for various reasons, most importantly to preclude "failure" as with an inherently more benign design, regardless of changes in conditions or circumstances, the intrinsic nature of the system cannot fail [26]. Furthermore, in those cases in which the inherent nature of the system is predefined, the system can be improved through changes in circumstances and conditions or the adoption of an alternative system.

This is also implied in safety science where as to plant design a manufacturing process is seen as inherently safer if it reduces or eliminates the hazards associated with materials and operations used in the process, and this reduction or elimination is permanent and inseparable [27]. This can be done through (a) *minimize*—use smaller quantities of hazardous substances; (b) *substitute*—replace a material with a less hazardous substance; (c) *moderate*—use less hazardous conditions, a less hazardous form of a material, or facilities which minimize the impact of a release of hazardous material or energy; (d) *simplify*—design facilities which eliminate unnecessary complexity and make operating errors less likely, and which are forgiving of errors which are made. The inherent safety approach aims to prevent the possibility of an accident, in contrast to secondary prevention which reduced the probability of an accident and mitigation which reduced the seriousness of an accident [28].

In the field of green chemistry, the focus of inherency is on substances and the form of a substance used in a chemical process. They should be chosen so as to minimize the potential for chemical accidents, including releases, explosions, and fires, but also designed to possess little or no toxicity to human health and the environment [29]. In the field of chemical regulations, Chapman [7] has suggested to refocus the regulatory assessment of chemicals from risks to riskiness by looking at the basic capacities of a chemical to cause harm [7]. Similarly, Reijnders [30] discusses inherently dispersive applications of nanoparticles and suggests the development of containment procedures and that nanoparticles are designed to be biodegradable and surface modified into low hazard compounds.

Different approaches exist which include the concept of inherency. Building on these different approaches and the previous discussion on risk management policy options, the goal of the proposed inherency risk analysis is to utilize inherency as a design principle that can systemically assess risks on different levels whether it is regarding a substance, product, process or system.

2.2. The inherency risk analysis stages

The inherency risk analysis consists of three main stages. Each stage may be repeated when considering alternative options and each repetition produces a 'Technology Option set' (TO-set). One could therefore have several different TO-sets at each stage. A TO-set can scrutinize an agent on different levels: the agent can be an object (substance, product, material, synthetic chemical, etc.), a procedure (industrial process, handling operation) or a system (e.g. transportation system, energy system etc.). In the IRA, the first stage focuses on the original agent subject to investigation, the second stage focuses on identifying technological options whereas the third stage is the decision making stage where the different alternatives are reviewed in terms of which alternative has the most attractive tradeoffs between costs and inherent safety. This is then used as a fundament for deciding which technology option to pursue.

2.2.1. Stage I

The first step of stage one summarizes the main characteristics of the original agent under investigation. By investigating the basic characteristics of the agent, such capacities to cause harm may be predicted. If for example the agent under scrutiny is a synthetic chemical, should characteristics such as persistency, bioaccumulation and mobility be investigated as a part of a base set as they can be seen as amplifying factors for a potential risk.

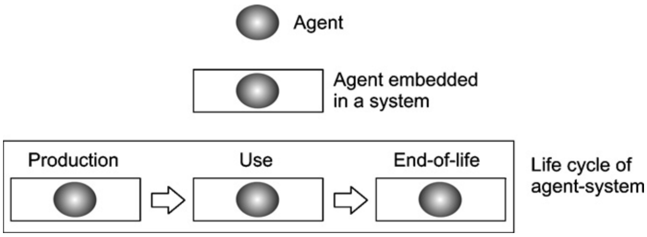

Fig. 1. Agent–system interactions in a life cycle perspective.

In the second and third step the IRA maps out the agents' functional advantages and disadvantages respectively. This is done in order to create focal points for suggestions on modifying or substituting the agent in the fifth step. It can also be possible to identify characteristics that do not contribute or only slightly contribute to the function, and which then should be a focus of closer scrutiny in order to simplify the agent.

As a fourth step, the IRA considers whether the agent has characteristics that have in some way a capacity to cause harm. This is especially reflected on the information gathered in steps 1–3, which are seen in its relative capability to cause harm. The capacity to cause harm should be reviewed along the life cycle of the agent. Important to reflect on are also which conditions along the life cycle that allow for high exposure to humans or ecosystems. The life cycles of materials and energy begin with acquisition (e.g., mining, drilling, harvesting) while the product cycle starts at the research and development (R & D) stage and move throughout manufacturing, distribution, use, and end of life. According to the definition of the agent, it may be a substance, but also a system. Depending on the scope of the IRA performing actor and the agent under consideration, it may be important to differentiate between (a) the capacity to cause harm that is a result of the inherent quality of the agent and (b) the capacity to cause harm that may result of the agent being used in a specific situation, i.e. the agent's application within a system. It may also be necessary to take into account the different life cycle stages of the system as illustrated in Fig. 1. Thus, one may have different matrixes such as illustrated in Table 1 for the agent and the agent within a system. This differentiation may assist in identifying what are inherent risks of the agent and what are inherent risks resulting from the system.

After identifying the agent characteristic, the fifth and last step focuses on whether the characteristics can be altered so the capacities to cause harm will be eliminated or reduced. Win–win situations are sought which optimizes the functional advantages and strive to reduce the functional disadvantages. For each alteration, steps 1–4 of Stage I will be repeated and the information

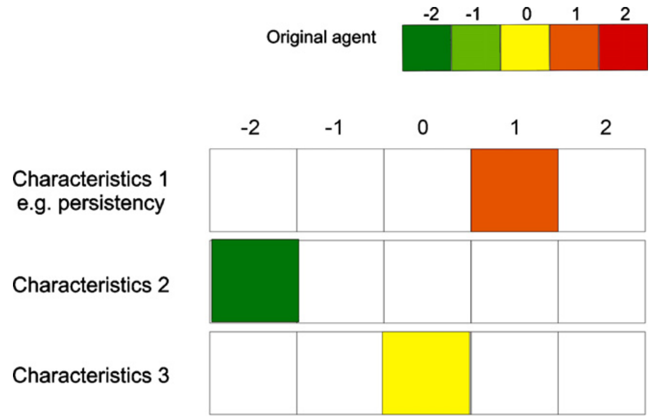

Fig. 2. Comparative risk analysis.

updated. The information may be summarized in a matrix which may look like Table 1. The alterations should always be compared (benchmarked) to the original agent, for example, by evaluating whether the alternative agent is more, equally or less toxic than the original agent (see Fig. 2). For example, a scale from −2 to 2 where 0 represents no difference could be used, but it is important to transparently describe the assumptions behind this assessment. This step can utilize comparative analyses such as relative risk and ecological assessment, thereby limiting the need for extensive and costly analyses based on quantification of variables. It is therefore also less sensitive to initial assumptions. At the end of step 5, there may be many different matrixes summarizing the information. Such a matrix may also be called a technology option set. If many different TO-sets have been developed, it may be necessary to apply a screening step in order to reduce the number of TO-sets to a manageable number. The screening should take into account the functional advantages/disadvantages and group or select the most attractive TO-sets.

2.2.2. Stage II

Stage II focuses on the question whether the function can be obtained with an alternative technology. It goes beyond modifying the existing agent, by searching for completely different technology options. The technology options can also be identified from other industrial sectors. One example is designing environmentally benign and sustainable personal transportation where Stage I may identify ways to modify a gasoline-powered system, but the aim of Stage II is to consider different technology options, such as the electric car. When a technology option is identified, the steps of Stage

Table 1
Stage I—TO-sets, various technology option sets may be produced depending on the number of moderations or alternatives identified.

Agent: agent under consideration				
Step 1: characteristics	Step 2: functional advantages			Step 3: functional disadvantages
Characteristics 1	...			...
Characteristics 2	...			...
etc.	...			...
Step 4: capacity to cause harm				
Life cycle stage	Health/safety impacts			Environmental impacts
	Workers	Consumers	Others	
Research & development/acquisition				
Manufacturing				
Distribution				
Use				
End-of-life				

Table 2
The tradeoffs of a technology option set (Adapted from [2]).

Agent: agent under consideration			
Group	Economic effects	Health/safety effects	Environmental effects
Producers	Net costs, $C_\$$	Benefits	
Workers	Net costs, $C_\$$	Benefits	
Consumers	Net costs, $C_\$$	Benefits	
Others	Net costs, $C_\$$	Benefits	Benefits

I are conducted. When no more technology options can be identified, Stage II closes. At the end of Stage II, several technology sets are identified with each technology option described in a matrix similar to the one illustrated in Table 1. Brainstorming exercises are very useful for Stage II and representatives knowledgeable for all life cycles stages of the agent under consideration should participate. External stakeholders may also be very beneficial to this procedure as they often bring in external knowledge about alternative technologies that enriches this exercise. As in Stage I, it may be necessary to apply a screening step.

2.2.3. *Stage III*

The third stage is the decision making stage. Before this stage starts, one may have to do a selection or clustering of similar TO-sets identified in Stages I and II in order to reach a manageable number of TO-sets. Based on the range of different solutions identified in Stages I and II, the tradeoffs between costs and environmental health and safety effects are estimated for the different technology alternatives. This procedure is also called tradeoff analysis and was first presented by Ashford [2] in relation to environmental impact analysis of regulations. Each alternative will produce a different looking matrix where the consequences for different actors can be visualized as illustrated in Table 2. The table compares the respective net costs and benefits of the different technology options, already identified in Stages I and II. Net costs, $C_\$$, are noncontroversial dollar values such as profits, wages, and medical costs, or estimates of the costs of compliance. Health and safety benefits can be quantified but are difficult to monetize or compare, such as, incidence of disease and changes in longevity, morbidity, probability of harm, or reduction in nonfatal injuries and diseases. Environmental benefits include preserving species, or reduction in mining impacts due to recycling. The monetarized environmental costs such as those reflected in loss of property value or costs of end of life treatment are included in the net costs, $C_\$$. The actor group producer may, in addition to the IRA performing company, also include other companies with contractual relationships to the IRA performing actor, i.e. downstream or upstream in the supply chain. The group others contains actors without contractual or commercial relationship with producers, workers or consumers.

By the help of the matrixes visualized in Tables 1 and 2, all alternatives in regards to their inherent risks, benefits and costs have been described. This systematic and transparent procedure creates a knowledge basis for deciding which technology solution is the optimal one to pursue in regards to environmental health and safety and the respective costs.

2.3. *Case study*

A producer wants to have added a special logo for their anniversary on a specially produced part composed of ABS plastic. The design department has identifies their esthetical requirements of the logo, e.g. silver shine and size. The engineering department identifies different alternatives, using the IRA to structure the information.

The engineering department starts at first stage and sets up a TO-set on a sample received and which is illustrated in Table 3. Table 3 reveals a number of issues subjected to review and the following modifications of the characteristics of the agent may be proposed: the inherency risk of PUR is related to isocyanate release which can be reduced by the use prepolymers or blocked isocyanates instead of monomeric isocyanates where MDI is preferred to TDI due to lower vapor pressure. For PVC heat stabilizers, alterations may be calcium/zinc compounds or barium/zinc compounds instead of lead and cadmium and trimellitates such as TOTM as additives for high temperature applications instead of chlorinated paraffins. Another TO-set with these modifications is then created.

The second stage asks whether the function can be obtained with an alternative technological solution. The engineers iden-

Table 3
Case study of logo, illustrative example of Stage I, TO-set.

Agent: *logo printed on Polyvinyl chloride (PVC) foil, polyurethane (PUR) surface treatment, Polypropylene PP glue*		
Step 1 characteristics	Step 2: functional advantages	Step 3: functional disadvantages
A glass clear, acrylic-based adhesive for maximum sunlight and weather resistance	High tensile strength films	Recycling not true
Good initial tack and ultimate adhesion. Resists high temperature	Excellent solvent and chemical resistance, ageing weathering and UV radiation Excellent adhesion to a wide range of substrates High transparency	Text not clearly visible from some angles as print is “buried” under the PUR

Step 4: capacity to cause harm				
Life cycle stage	Health/safety impacts			Environmental impacts
	Workers	Consumers	Others	
Research & Development /acquisition				
Manufacturing	High level of isocyanates is liberated in production of PUR.			Release of isocyanate in production of PUR.
Distribution				
Use		PUR: liberates isocyanates if accidentally heated up, (inhalation risk). PVC may contain additives leaching such as lead, cadmium or chlorinated paraffins		Possible leaching of PVC additives. Possible liberation of isocyanate in accidents (e.g. fire).
End-of-life				Recycling not true. mix of plastics. To avoid leaching, PVC has to be specially incinerated to collect hazardous additives.

Table 4
Case study of logo, illustrative example of Stage III, tradeoff analysis.

Agent: logo made out of ABS plastic			
Group	Economic effects	Health/safety effects	Environmental effects
Producers	$+C_\$$ increase for tooling		
Workers	$-C_\$$ reduction in medical bills	Reduction in respiratory diseases.	
Consumers	$-C_\$$ reduction in medical bills	Reduction in respiratory severity of accidents (e.g. fire).	
Others	$-C_\$$ of material value at end of life		Recycling true. Reduction in environmental pollution

tify the possibility of integrating the logo into the component by using the same material as the parent component, ABS. This reveals several advantages, including avoiding the risk of leaching chemicals and additives as well as that recycling now can take place of the whole component and no disassembly has to take place. The TO-set for this alternative is then produced and the different alternatives are given for the purchasing department to evaluate costs.

Third stage, illustrated with one of the TO-sets in Table 4, reveals that there are more economic costs associated with tooling for the ABS solution but reduced cost in the disposal of the component, as well as health, safety and environmental benefits related to avoiding leaching of additives. The original agent has less initial economic costs associated, but increasing costs in the disposal as well as environmental impacts on the actor groups consumers and workers as well as the environment. In addition, costs related to the brand may occur as a result of potential negative media focus on this design solution. After comparing the different alternatives the technology solution in Table 4 is finally decided favorable by the management.

3. Discussion

3.1. Handling novelty and uncertainty in IRA

The decision makers performing the last stage of the IRA should also take into account the lack of knowledge which is often characterized by novel agents. Novelty means that we do not have experience with how it behaves or how we should behave toward it and thus have insufficient knowledge to rule out that the agent causes harm [7]. This does not mean that we cannot cope with novelty. For example in some cases we do not cope with the effect of the agent itself, but with the exposure to the agent. However, novelty can relate to a novel design but the use of traditional materials, or have a traditional design with novel materials. Both should be considered when looking for technology options and transparently described in the matrix. Uncertainties are therefore fully described in the matrix. The question is always how may risk managers deal with insufficient information? The decision maker has to consequently decide whether it wishes to treat the agent under scrutiny either as *if* it were severely persistent, as *if* it were moderately persistent, as *if* it were not persistent etc. The assumptions regarding the inherent characteristics made in Stage I, step 4 and 5, can be called a (regulatory) default. Treating a substance in general as if it were effectively dangerous can be called a precautionary default [31]. New data and increasing knowledge has always the potential to motivate departures from such defaults. The inherent risk can as such be reduced by selecting technology options where more is known about cause–effect relationships.

3.2. Who should be conducting the IRA and how could this information be utilized for various stakeholders?

Which party that is conducting the IRA is important and has implications in regards to the information they have available for basing their decisions. Stages 1 and 2 should be conducted by the industry responsible for the agent. Upon the information gathered in Stages 1 and 2, the decisions are made in Stage 3 on which TO-set to pursue. However, it may be totally different people that are providing the information in Stages 1 and 2, which could be representatives for lower management or research and development, and those that are making the decisions in Stage 3, which could typically be senior managers. However, small firms and especially start-up companies have often limited capacity and knowledge outside their own technology area. These companies are driven predominantly by severe time, expertise and material resource constrains and cannot afford to hire environmental experts [32]. As these companies may lack confidence or knowledge to recognize environmental benefits, a possibility could be to establish "technology transfer & innovation centers" supported by for example the industrial organizations and/or regional government. Such centers could among others have the task to facilitate and aid in the search for alternative technologies. It is well to remember that small and medium-sized enterprises are believed to be collectively responsible for a significant proportion of industrial pollution and for more environmental damage than larger companies [32]. Larger companies have more resources and thus should, in principal, have a higher capacity to conduct IRA.

The information in Stages 1 and 2 could be useful for other parties as well. For example a customer or downstream user may request and collect information on Stages 1 and 2 from various sources in the supply chain in order to make strategic supply chain purchasing decisions. The importance of supply chain management for improving environmental conditions are well established and more thoroughly discussed elsewhere (see e.g. [33–35]).

One may also imagine a regulatory system where the regulatory agency may request to see the IRA on which a TO-set is decided on from industry. This could possibly replace the much debated BAT standards and reduce some of the innovation barriers that BAT standards create and in this way ensure that new innovations have a better possibility to gain access to the market. The regulatory agency could verify the information provided and it would be the firm's responsibility to convince the regulator that the firm has undertaken a thorough investigation in the potential technology environmental health impacts and has in this respect searched for the superior technology option. The firm's decision on how to pursue this particular technology option is therefore well documented and the firm could then be given a license to operate.

3.3. How to reduce the number of technology option sets to a manageable number?

The generation of technology alternatives is by design researchers characterized as the divergent step, which is followed by a convergent step where the alternatives are reduced to a small number of feasible options [36]. It is not feasible for time and cost reasons to consider all potential options even though if simplified evaluation approaches are applied [37]. Screening steps at the end of Stages I and II can therefore be seen as valuable tools to reduce the number of TO-sets. There are often two conflicting goals involved;

the generation of different TO-sets must go for the widest possible range of solution so as not to ignore a number of possibilities that are based on alternative principles, but at the same time the minimum possible number in order to be manageable. Furthermore, when one abstract solution is converted into a more detailed solution, alternative possibilities occur which should also be taken into account. Therefore, the number of different conceptual designs must be reduced at the earliest possible opportunity because in engineering design practice, one cannot consider a great many concepts in detail [38]. Therefore when the TO-sets are detailed enough to be considered against the major requirements, the number of solutions should be deliberatively decreased (this does not mean they are discarded as it may be necessary to backtrack to them). Such requirements should particularly take into consideration the functional advantages/disadvantages of the TO-set under scrutiny.

3.4. Net costs calculations

Once a high-priority selection have been made of the TO-sets developed in Stages I and II, Stage III focuses on calculating the costs and benefits of the various options. However, net cost calculations may not be entirely straightforward. There are in general two potential approaches: *quantitative* evaluations, which rely on empirical data and *qualitative* evaluations, which are based on observation and judgment. Often, both approaches are taken. For example, environmental costs and benefits are quantified when possible within the project budget and schedule such as disposal costs of particular materials or treatment costs of hazardous waste, but qualified evaluations are used for e.g. calculating improved employee satisfaction by switching from a hazardous compound to a non-hazardous. Several techniques and examples for environmental net cost calculations can be found in the literature regarding green supply chain management and environmental accounting (see e.g. [39–41]). The literature further points to businesses that in terms of supply-chain management have increased their competitiveness by engaging in environmental performance-enhancing activities such a total inventory levels reduction, decreased product obsolescence, decreasing costs associated with material losses or handling of hazardous materials, and increased revenues by converting from waste to by-products. In particular is the financial pay-off of the avoidance of environmental liabilities important to take into account. Businesses can prevent or reduce environmental liabilities by paying attention to environmental aspects and translating the liabilities into monetary terms in order to establish them as a part of financial evaluations [42]. However, important to keep in mind is that costs can also occur to external stakeholders and that you may have relationship costs or image costs in this respect. In Table 2, an example of such an external net cost occurring may be a disposal fee to consumers.

4. Conclusion

Current risk assessment procedures are time and resource consuming and, as a result, become procedures that companies normally will not comply with, unless legally enforced to do so. By combining risk assessment with a structured approach to identify superior technology options within a risk management system, the result could very well be a win–win situation for both companies and the environment. Technology options implicating less inherent risk potentials are also less likely to become a liability. The inherent risk analysis may also be a systematic tool in order to identify opportunities for industry to innovate as they become aware of potential technology gaps.

Box 1: Inherency risk analysis procedure
First stage

(1) What are the characteristics of the subject under analysis?
(2) What are the functional advantages of the characteristics of the subject?
(3) What are the functional disadvantages?
(4) How may these functions impact environment and human health in a life cycle perspective?
(5) Can these impacts be reduced by changing the characteristics of the subject?
(6) Repeat first set until no more moderations can be identified
(7) If necessary, apply a screening step to reduce the number of TO-sets.

Second stage:

(1) Can the functions be obtained by alternative technological solutions?
(2) If yes what are the inherency factors of the alternative (repeat first set)
(3) Repeat second set until no more alternatives can be identified
(4) If necessary, apply a screening step to reduce the number of TO-sets.

Third stage:

(1) What are the tradeoffs between costs and environmental health and safety effects for the different technology alternatives?
(2) Based on the range of identified alternative solutions for the function—which solution has the most attractive tradeoff between inherent safety and costs?

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